THE ABSENCE OF WATER IN CERTAIN SANDSTONES OF THE APPALACHIAN OIL-FIELDS

BY

FRANK REEVES

A DISSERTATION

SUBMITTED TO THE BOARD OF UNIVERSITY STUDIES OF THE JOHNS HOPKINS UNIVERSITY IN CONFORMITY WITH THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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FRANK REEVES.

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INTRODUCTION.

The petroleum-bearing sandstones of the Catskill formation of the Devonian system in the Appalachian oil fields in southwestern Pennsylvania and West Virginia to all appearances contain no water. The fact that the oil sands of Mississippian age overlying these contain an abundance of saline water led to the conclusion at first that the absence of water in the deeper oil sands was due to factors functional of their depth. With the sinking of deeper shafts in mining operations the facts revealed seemed to substantiate this belief, so that Van Hise's and other early geologists' hypothesis, that water occurs in the earth's strata down to 10,000 meters or to a point where no porous area could persist under the great pressure of the weight of the superincumbent strata, was replaced by the belief among many geologists that below depths of from 1,500 to 2,000 feet little or no water occurs. Many metalliferous geologists have held to this belief and in sup-

port of it have cited the absence of water in the lower levels of many deep mines.

In the following discussion, however, it will be pointed out that the idea that the absence of water in the oils and under discussion is due to factors functional of depth is based on a wrong hypothesis and that their dryness instead is a result of the unusual geological conditions under which they were deposited.

The facts revealed by deep drilling in fields outside of the Appalachian region indicate that there is no general disappearance of water with depth. With the exception of local areas in Wyoming and Utah, water has been encountered in all the oil fields of the world at all depths to which the drill has penetrated, wherever the conditions of structure and porosity are favorable. In many areas in Oklahoma and California, the oil sands are reached at greater depths than in the Appalachian fields, yet in these deep sands water is encountered in copious amounts. Even in the Appalachian field itself two wells recently drilled to great depths have encountered prolific water-bearing formations below the dry sands. This would appear to be more reliable data on which to base a conclusion as to the water content of the earth's strata as a whole than that furnished by deep mines which Kemp[1] and others cite as evidence that water disappears at shallow depths, since most deep mines are in areas where igneous intrusions have brought about a recrystallization and cementation that to a great extent have destroyed the pores of the strata and displaced the water.

Before considering the problem of the absence of water in the strata in question it will be necessary to describe briefly the broad geologic relations of the area, especially in regard to its structural and stratigraphic features.

DESCRIPTION OF THE AREA.

Areal Geology.—The Appalachian oil field lies in a geosyncline which is generally known as the Appalachian coal basin. The surface strata over the greater portion of the basin are of Penn-

[1] Kemp, J. F., "Waters Meteoric and Magmatic," *Mining and Scientific Press*, Vol. 96, pp. 705–708, 1908.

sylvanian age with a small area of Permian beds still extant in its middle (see Fig. 9). Around the edges of the basin strata of the Mississippian and Upper Devonian outcrop. Consequently the oil sands of these series reach the surface on the eastern side

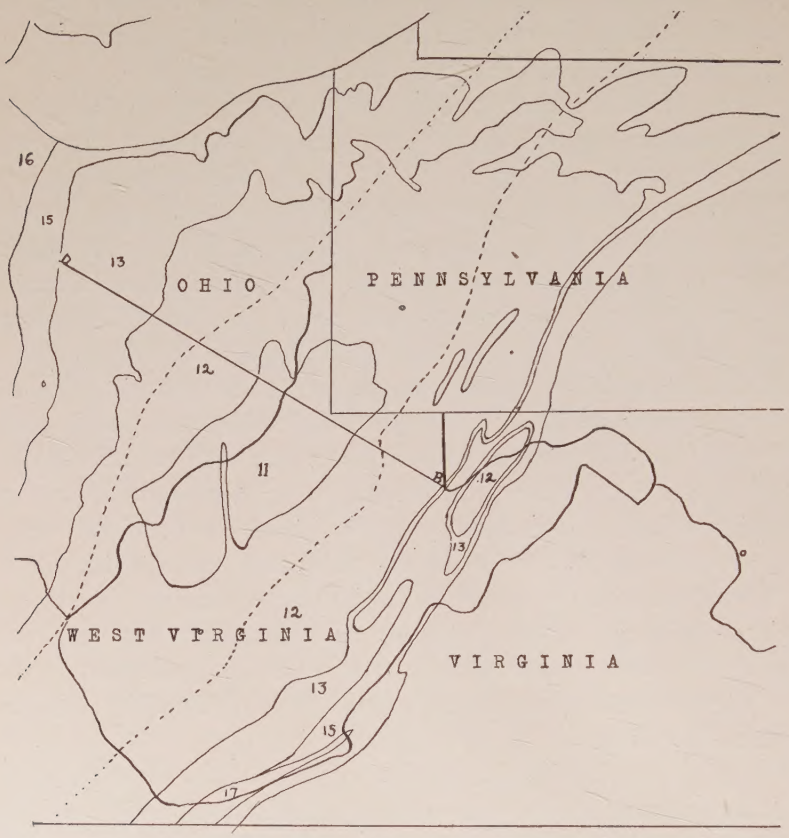

FIG. 9. Geology of Appalachian Oil Fields. 11, Permian; 12, Pennsylvanian; 13, Mississippian; 15, Devonian; 16, Silurian; 17, Ordivician.

of the basin along the Allegheny front and on the western side in central Ohio. The same strata outcrop around the northern end of the basin in northwestern Pennsylvania.

Structure.—The rocks are but slightly folded in the area under consideration. They dip toward the broad middle part of the basin in West Virginia from the north, east, and west. From

the Allegheny front westward the general dip is interrupted by three or four folds, which become less and less accentuated and in which the strata attain lower and lower levels as they approach the middle part of the basin. Across this occur four or five minor flexures which are continuous over most of the area except in central West Virginia, where the normal structure of the basin is destroyed by a major fold of considerable magnitude, which runs north and south for thirty miles. The minor folds above mentioned have a general southwestern strike conforming to the normal alignment of Appalachian mountain folds. These folds vary in width from 6 to 8 miles. The strata in the anticlinal crests reach an altitude of from 200 to 500 feet above that attained in the

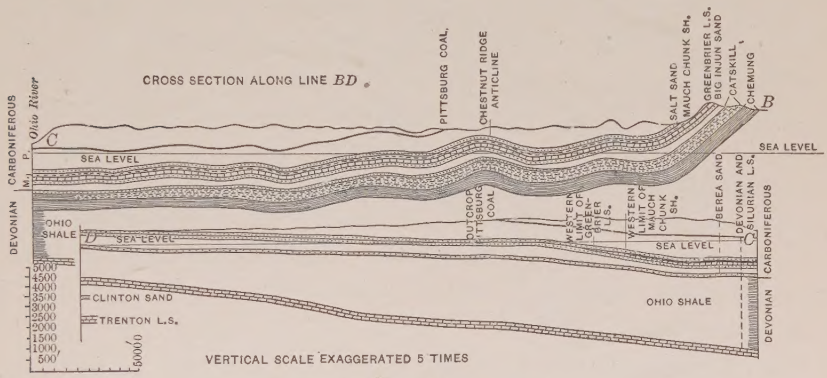

FIG. 10.

synclinal areas. Thus the dip is between 50 and 100 feet to the mile. From the Ohio River westward, the strata rise gently to their outcrop in central Ohio without any interruption except for structural terraces and an occasional slight fold. The structure of the northern part of the Appalachian coal basin is shown in Fig. 11.

The water content of the basin north of Pittsburgh is not considered here, as the data is rather confusing, owing to the fact that the oil fields of this area were developed twenty years before those farther southward and water in many areas has penetrated the sands through old abandoned wells and destroyed the normal water conditions of the sands. For the same reason no discussion

is given of the water content of the shallow sands of the Pennsylvanian series in the area here considered, as they lie more or less in the zone of circulating ground water and contain water unlike that in the deeper sands. Thus the discussion is limited

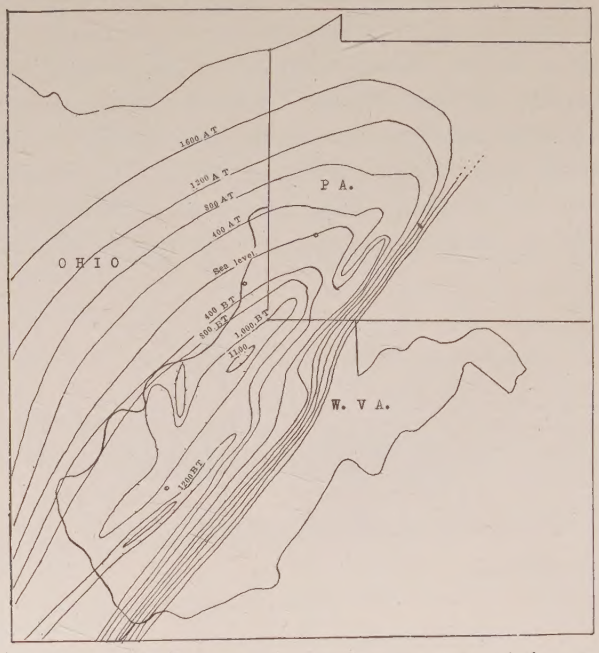

FIG. 11. Contour on Big Injun sand, showing structure of the northern part and Appalachian coal basin.

chiefly to the water content of the Mississippian and Upper Devonian strata of that part of the basin which underlies southwestern Pennsylvania and West Virginia.

THE OIL SANDS AND THEIR WATER CONTENT.

Sands of the Mississippian Series.—This series consists of from 600 to 800 feet of strata comprising three formations, the Mauch Chunk, Greenbrier, and Pocono. The first of these is a shale with a lenticular sandstone facies which when oil-bearing is known as the Maxton sand. The Greenbrier in most areas is represented by a limestone member of from 75 to 200 feet in

thickness. It is absent only in the northern part of the geosyncline where it has been removed by pre-Pennsylvanian erosion. The limestone is too compact to hold either oil or water except in local areas in southeastern Ohio and southwestern West Virginia. The formation is known in the oil fields as the "Big Lime." The Pocono formation consists of sandstone and shale. The Pocono sandstone which varies from 100 to 250 feet in thickness, lies at the top of the formation. This is the Big Injun oil sand. It is widespread in occurrence and rather uniform in thickness over great areas. Below this sandstone there are several hundred feet of shale beneath which is the Berea sand which is from 5 to 50 feet in thickness. At the base of the Mississippian is the Hundred-foot sand which underlies the Berea from 50 to 175 feet, the intervening strata being composed of shale. This sandstone is developed southward only a short distance beyond the southwestern corner of Pennsylvania and in that regard is similar to the Upper Devonian oil sands.

The oil sands of the Mississippian series are, generally speaking, water-bearing. They however do not contain water throughout their whole distribution. In most areas, there is a structural arrangement of the water, oil, and gas, the water occurring in the synclines, the gas in the anticlines, and the oil occupying an intermediate position. With a variation in the amount of water in the sand this arrangement is altered. With an increase in amount of water the oil is forced further up the flanks of the anticline so that where the sands are "saturated" the oil occupies the anticlinal crests. When such conditions are present the water and oil occur together, the water generally occurring in much greater quantities than the oil. Where there is no water in the sands the oil usually occupies the synclinal areas.

Sands of the Catskill Formation.—Below the Hundred-foot sand occurs a series of red shales and thin reddish or white sandstones which comprise the Catskill formation. No certain line can be fixed for the base of this formation for the criteria on which it is separated from the underlying Chemung is the lower limits of red material, which varies from place to place. Eastward along the outcrop the formation consists of from 600 to

900 feet of alternating layers of shale and sandstone, red and green in color, which are unfossiliferous and in places sun-cracked and ripple-marked. The shale is both arenaceous and argillaceous and contains about 6 per cent. of ferric oxide. The sandstone is composed of a medium-grained, grayish-white siliceous material. On account of these features and the predominant red color the Catskill can be definitely separated from the conglomeratic Pocono sandstone above and the olive-green, fossiliferous shale of the Chemung below. West of the outcrop

FIG. 12. Catskill Sands. *GH*, Outcrop of Catskill Formation; *AB*, Western Limit of Sands; *EF*, *RS*, Areas Containing Red Beds; *CD*, *MN* Areas Containing Water.

in the counties of southwestern Pennsylvania and northern West Virginia these sandstone members are important oil and gas bearing sands. Named in descending order they are: the Thirty-foot, Stray, Gordon or Third, Fourth, Fifth, and Sixth or Bayard sands. West and south of the line *AB* indicated on the map (Fig. 12) these sandstones, as well as the intervening red shale, are replaced by dark shale. The sandstones themselves are very similar

in color, texture, and composition to the oil sands of the Mississippian series. However, in thickness and persistence they differ, being thinner, seldom attaining a thickness of more than 50 feet and usually averaging about 25 feet. They are also more lenticular than the Mississippian sands. Towards the eastern outcrop they become less and less definite units. The intervening shale members make up almost twice as much of the formation as the sandstones and average about 50 feet in thickness. The Catskill sands with the overlying Hundred-foot sand comprise the Venango oil sand group which produces the most of the oil of southwestern Pennsylvania. Possibly the most important commercially and the most persistent is the Gordon sand. It occurs about the middle of the formation and underlies the Big Injun sand about 800 feet and the Pittsburgh coal 2,100 feet. It ranges in depth below the surface throughout the central part of the basin from 2,000 to 3,000 feet.

Sands below the Catskill.—Below the Catskill there are a few oil-producing sands in the Chemung but these occur farther northward in Pennsylvania and New York. In the area under consideration many wells have penetrated the Chemung but usually nothing is encountered but close-grained shale. Here and there gas has been found in the Speechly sand which occurs about the middle of the formation. Two wells, mentioned above, have gone to greater depths and have penetrated strata below the Chemung. One[2] drilled in 1912 near Charleston, West Virginia, passed through 2,840 feet of shale below the Berea sandstone and encountered the Lower Devonian limestone in which a big flow of saline water was found at a depth of 5,592 feet below the surface. Another well,[3] near McDonald, Pennsylvania, penetrated the Lower Devonian limestone 4,386 feet below the Berea. At a distance of 252 feet below the top of this limestone and at a depth of 6,260 feet a sandstone, possibly the Oriskany, was encountered which contained a concentrated brine which rose 4,000 feet in the well.

[2] Introduction, Kanawha County Rept., W. Va. Geol. Survey, pp. 1–5, 1914.

[3] White, I. C., "Note on a Very Deep Well near McDonald, Pa.," *Bull. Geol. Soc. Amer.*, Vol. 24, pp. 215–282, 1913.

With the exception of the water found at the above-mentioned horizons, little is encountered below the Carboniferous except in some areas of very local extent. The dryness of the Catskill sands was noted early in the history of the oil industry and as stated above was attributed to the depth at which the sands were found. But, as will be shown, it is due to other causes.

EVIDENCE OF DRYNESS OF SANDS.

It appears necessary here to consider the evidence of the dryness of the sands, for although it has long been a seemingly well-established fact that the sands of the Catskill in the area mentioned are free from water, yet many geologists think that this dryness is only apparent and that in reality they contain water. Thus Munn[4] states that water is present in all sands, but on account of its static state in strata below the zone of circulating ground waters, it is under no hydraulic head and hence does not enter the bore hole. Shaw[5] offers the argument that these deep sands do not yield any water because they are more nearly sealed than the sands at less depth and hence when they are penetrated by the drill no water enters the well because if it did a vacuum would be left in the sand. Others insist that the non-appearance of water in the wells is due to the compactness of the sand or to structural conditions. Some argue that hygroscopic water is present and hence that these sands are not dry. But this is beside the point, for what is meant here by dryness is an absence of free water in the sand in sufficient quantities to appear in the wells when the sand is penetrated by the drill. Thus, in reality, it is a comparative term, but to be exact, no rock in its native condition is entirely free from moisture. The difference, however, between the water content of most oil sands, where water occurs at least in the synclines, and that of a sand where no water appears in any part of its distribution, shows a sufficient contrast to apply to the latter the term of "dry sand."

[4] Munn, M. J., "The Menifee Gas Field and the Ragland Oil Field, Kentucky," Bull. U. S. Geol. Survey, No. 531*a*, p. 26.

[5] Shaw, E. W., "Discussion of Roswell Johnson's paper on the Rôle and Fate of Connate Water in Oil and Gas Sands," *Trans. Amer. Inst. Min. Eng.*, Vol. 93, pp. 221–227, February, 1915.

In considering the explanations of Munn and Shaw, the fact need only be mentioned that water has been found below the Catskill sands in the two wells mentioned above, to vitiate the force of their arguments as they are based chiefly on the factor of depth. The fallacy of these explanations is also apparent when it is pointed out that the impelling force which generally drives water into the well is gas pressure and not the force resulting from hydraulic movement or the hydrostatic head of the water. Again, it is impossible to explain why oil should flow into a well and not water, for it is improbable that small bodies of oil could be moving around in the sand independently of the water. A flow of oil in a bore hole would also create as much of a vacuum in the sand as a flow of water, yet throughout thousands of square miles, where it is claimed that no water will enter these sands because there is no hydraulic force or where the sand is too nearly sealed, oil appears freely, and yet oil is more viscous than water and hence would have a greater tendency to remain in the sand than the water. Again, if the sand is porous enough to yield oil it is of sufficient porosity to yield water. It is impossible that the water should always occur in the compact areas and the oil in the porous areas. This might be possible in a horizontal sand, for often under such conditions the oil occupies the most porous layer, the water occurring in the rest of the sand. But in areas where there are definite folds there is a structural arrangement of the oil and water, independent of the porosity of the sand, with the water, for the most part, occupying the synclines. Instead the oil pools in the sands of the Catskill formation usually occur in the synclines, which is in striking contrast to the structural occurrence of oil in most other fields of the world where oil generally occupies anticlines or structural terraces.

The evidence upon which the argument for dryness is based is not obtained from a local area. Througout all southwestern Pennsylvania and northern West Virginia these sands have been penetrated by the drill, in an area of at least 10,000 square miles. Across this area there are about five parallel folds and thousands of wells have tested the synclines as well as the anticlines with the result that oil and gas have been found in numerous localities.

Many of the oil wells have been of the gusher type, that is, oil is forced out of the wells by gas pressure which occurs in the sand back of the oil, but with the exception of two local areas, no water has appeared. This, coupled with the fact that the oil occupies the syncline, makes it appear as a proven fact that these sands contain no free water.

PROBLEM—THAT OF THE DISAPPEARANCE OF CONNATE WATER.

With the absence of water in the Catskill sands reasonably established we may next consider whether this absence is due to the disappearance of connate water or to the non-appearance of meteoric water. This of course raises the much-debated question of the origin of oil brines, for if these brines are connate then the present problem is the explanation of how the Catskill sands became depleted of their water of deposition. If, on the other hand, such brines are meteoric in origin then it becomes necessary to explain why meteoric water has not penetrated the sands. Considerations of these problems suggest that the brines are connate, for there is at present no satisfactory explanation of how the water occluded with sediments may have been removed from them in an area that has undergone as little deformation and metamorphism as the strata of the above-described geosyncline.

FORMER EXPLANATIONS.

The explanations usually offered for the disappearance of connate water through processes of hydration of minerals, consolidation of sediments, expansion and evaporation of the water due to heat and drainage as a result of elevation, are not adequate to explain the phenomenon, as may be briefly pointed out.

There are few minerals in sedimentary strata capable of uniting with water, and these would be more likely to be hydrated when they were being transported as water-borne sediments than while subjected to the dehydration forces of pressure and heat consequent to their position in deeply buried strata. Again, the factor of consolidation of sediments would not be effective because compression, though it might lower the porous areas of the sediments,

could not decrease the percentage of saturation and the porous area remaining would still be occupied by water. Heat apparently could have been no effective factor in removing the water, as there is but 4 per cent. increase in volume when the temperature of water is raised from 4° C. to 100° C., which is a much greater variation in temperature than is brought about in the change in earth temperatures in a geologic cycle. Heat could not, on the other hand, drive off the water by evaporation as the dry strata are everywhere covered with saturated rocks. Elevation apparently could not have resulted in drainage of the sands due to the synclinal structure of the basin. All of these explanations might be considered in greater detail but for the fact that the discovery of water at greater depths has shown that these ideas are untenable, as they are based chiefly on the factor of depth.

Johnson[6] has discussed the question of how water may be removed from strata by the compacting of the sediments, the formation of cement materials and the development of gas. These processes, he thinks, would have a tendency to decrease the pore space and to increase the amount of material to occupy it. Thus, in a sand of no great thickness some of the material would be forced out and, as the water is less viscous than the oil, it is displaced first by being driven upward through fissures and joints and by occupying the pores of the shale. It is difficult to understand how these forces are going to effect such a selective action, since under the pressures that would bring this about, the materials would have the same viscosity and surface tension. It is impossible to believe also that the water would migrate upward across several layers of sands and impervious shales leaving the oil behind subject to the pressure under which it is found.

PRESENT EXPLANATION.

Having noted that the explanations usually given for the absence of water in sedimentary strata are not adequate to explain the dryness of the sands under consideration, the problem was attacked on the principle that the absence of water was due to

[6] Johnson, R. H., "The Rôle and Fate of Connate Water in Oil and Gas Sands," *Trans. Amer. Inst. Min. Eng.*, Vol. 98, pp. 221–227, February, 1915.

processes which removed the connate water and not to conditions that prevented the entrance of meteoric water. Working on this hypothesis the following conclusion was reached: that the sediments were dried out after they were deposited as river-borne sediments and their porous areas filled with air which later prevented water from penetrating them during submergence beneath the sea.

Evidence that Air-filled Sediments Will Exclude Water.—This idea rests primarily on the principle that air-filled material will exclude water, and though this may appear improbable yet facts seem to substantiate it.

King[7] states that in arid regions or during dry seasons in more humid areas the soil will be dried out and be so filled with air that water will penetrate the surface with great difficulty. Whitney[8] says that water will not readily penetrate dry strata and cites areas where a rainfall of 50 cm. per year occurring at one season results in the water remaining within a few meters of the surface, while an entirely dry and dusty mass occurs adjacent to it. The following experiment also demonstrates the same fact.

A number of glass tubes ½ meter in length and 30 centimeters in diameter were two thirds filled with dry sands of different fineness. The upper third of the tubes were then filled with water. This water would in a few minutes saturate about 60 centimeters of the upper portion of the sand, displacing all the air, part of which was forced downward, the other part rising to the surface of the water in bubbles. Below the saturated zone no water penetrated except hygroscopic water, which did not reach the bottom of the tubes, except in the finer-grained sands. In some of the coarser-grained sands after a month had passed the materials in the lower portion of the tube were entirely dry, while in the finer-grained, though each grain might have a film of water around it, the space between the grains was unoccupied except by air. At the end of this time, water was still standing in the upper part of the tubes.

[7] King, F. H., *loc. cit.*, p. 93, 1897–98.

[8] Whitney, J. D., Weather Bureau, Bull. No. 4, U. S. Dept. Agriculture, p. 14, 1892.

Geological Conditions Under Which the Sands Were Dried.—The general character of the rocks of the Catskill formation suggest that they had an origin which would make such an explanation of the origin of the dry sands possible. Along its eastern outcrop this formation is composed of unassorted, unfossiliferous sandstones and shales which are almost entirely red in color and which are ripple-marked and sun-cracked. In the oil fields it is composed of white sandstone alternating with red and dark shales, while farther west the whole formation grades into a dark compact shale which contains marine fossils. This change in the lithology of the formation from east to west is explained by the fact that the rocks represent deposits formed along an oscillating shore line of the sea which occupied this area during most of Paleozoic time. In Upper Devonian time this sea was very shallow and was bordered on the east by a low coastal plain which extended to the highlands of Appalachia, still farther east. Over this low, flat-lying land rivers meandered which received their loads from the eastward land mass. During flood periods these rivers spread out over their flood plains, depositing the coarse material there or directly offshore, while the finer sediments were carried farther out to sea. During periods of little rainfall on the highlands the rivers did not occupy their flood plain and the sediments deposited there during the last period of flood were dried out and filled with air, which prevented water from entering them again when the next season of rainfall caused the rivers to leave their banks and cover the plain. Along the littoral zone the waves sorted the mud and sand, carrying the former farther out to sea and leaving the latter distributed as sand layers along the littoral zone. These materials not being exposed to the air were not oxidized or depleted of their water. But as the sea was shallow, slight movements caused by subsidence of the sea floor and oscillations of the land together with the silting up of the shallow continental sea brought about a constant oscillation of the strand line and hence there occurs throughout the area under consideration a complete interfingering of marine and continental deposits, the former being represented by dark shale and white sandstone and the latter by "red beds."

Such conditions would expose the sand to the action of the air and result in its desaturation with the formation of red sediments. With the transgression and recession of the sea the general coastal alignments due to the salient features of the land mass would persist and be apparent in the general distribution of the "red beds." Thus, a line drawn through the most westerly occurrence of red shale would show, approximately, the shore line during the greatest recession of the seas at that particular time. To the east of this line the sediments making up the stratum would have been dried out during this recession and exposure to the atmosphere.

On examining the data of the occurrence of salt water in a sand there is a striking relationship between areas in which there is no water and those in which the material directly overlying the sand contains no red color. This holds good not only for the Catskill but for sands in the Mississippian in which "red beds" occur, marking periods in which there were recessions of the sea, or a recurrence of the conditions which effected the deposition of the Catskill red beds.

DISTRIBUTION OF RED BEDS AND OCCURRENCE OF WATER.

The relationship between the distribution of red beds and the occurrence of water in the Maxton, Big Injun, Hundred-foot, and Catskill sands is represented in Figs. 13, 14, 15, and 12. These maps have been compiled from hundreds of well records published in the Bulletins of the United States Geological Survey and in the reports of the West Virginia and Ohio Geological Surveys, together with other records and data obtained by the writer from various oil companies operating in the Appalachian field.

In these maps the lines used to denote "red beds" and occurrence of water are to be considered as indicating areas, rather than as definite boundaries, for many things have to be considered in determining the wet and dry areas of a sand. The presence also of red shale in a drill hole is not always noted, yet this introduces uncertainty only in fixing the exact limits of

FIG. 13. Maxton Sand. *CD*, Eastern Outcrop; *AB*. Northern and Western Limit of Sand; *GH*, Eastern Limit of Water; *EF*, Western Limit of Red Beds.

FIG. 14. Big Injun Sand. *AB, CD*, Outcrops; *GH*, Eastern Limit of Water; *EF*, Western Limit of Red Beds Associated with Sand.

these areas, which as a whole are clearly recognizable. Thus, to the east of the dotted lines there is a definite occurrence of red shale and sandstone. In this region also there is a widely observed absence of water which is in striking contrast to areas to the west where the synclines almost invariably contain large volumes of water. This general distribution of water can in no way be explained by the structure of the basin as a whole. Eastward towards the outcrop of each sand, water is found in some

FIG. 15. Hundred-foot Sand. *GB*, Outcrop; *AB*, Western Limit of Sand; *AC, BD*, Areas Associated with Red Beds; *EHF*, Areas Containing Water.

wells but such water has comparatively little mineral matter in solution and is, apparently, meteoric water which has entered from the outcrop. Some of the relations of the "red beds" and the distribution of water may be best brought out by a separate consideration of each sand.

Maxton.—The Maxton, as noted above, is a sandstone facies of the Mauch Chunk shale. North and west of the line *A–B* in Fig. 12 this sandstone member is replaced by shale. A little

further west the shale disappears, being removed by erosion indicated by the unconformity previously mentioned. That part of *F–G* which passes through Allegheny and Westmoreland counties, Pennsylvania, is approximately the northern limit of the Mauch Chunk formation. East of the line the Mauch Chunk shale is generally red and in this area the Maxton sand is non-water-bearing, while to the west of *G–H* it contains a great quantity of water. This dry condition of the sand is borne out, also, by the structural position of the oil pools, which to the east occur in synclines, whereas to the west they occupy some part of the anticlines.

Big Injun.—The Big Injun sand underlies the whole area between its eastern and western outcrop and throughout the central part of this area it is an important oil, gas, and water-producing sand. The line *H–G* represents closely the eastern limit of the saline water which occurs rather widely distributed throughout the sand to the west. The non-occurrence of the water farther east is usually thought to be due to the general structural features of the geosyncline, for in the northern part of the basin this water line conforms very closely to the eastern edge of the central part of the basin. To the south this does not hold, as will be seen by reference to Fig. 11. In this area the Big Injun is reported often as a red sandstone, which is in a striking contrast to its white or gray color in most other areas. Also the oil pools found in this sand to the south occupy synclines. An occurrence of asphalt near Sago, Upshur County, associated with the red material in the Big Injun sand, adds further evidence that the absence of water in this area is due to the sediments of the formation being exposed to the air.

Hundred-foot Sand.—The Hundred-foot sand, as is indicated by line *A–B,* Fig. 15, does not persist far to the south or west. In the area included in the line *E–H–F* water occurs. The absence of water to the east of *H–F* may be due chiefly to structure as the strata at about this line begin to rise rapidly along the western flank of the Chestnut Ridge anticlines. Yet, the Hundred-foot sand contains red facies to the southeast and the dryness of the sand in this area may have been brought about by the condition

which produced the red shale. The relationship of red beds to the occurrence of salt water is more obvious in southwestern Pennsylvania, especially in Beaver County and western Allegheny and Washington counties where there is a general absence of water in the Hundred-foot sand, while further east water occurs in considerable quantities. Munn and Griswold[9] have associated this distribution of water with the structural conditions of the strata, yet it is notable that in the areas where no salt water occurs there is a considerable development of red shale above the sand and no red shale is noted in well records in the area where water occurs in the Hundred-foot.

Catskill Sands.—The Catskill sands, which comprise the Thirty-foot or Ninevah sand, Gordon Stray, Gordon or Third sand, and the Fourth, Fifth, and Sixth sands, will be considered together, as they all have about the same distribution and general absence of water. West of the line *A–B* both the sands and the intervening red shale are replaced by dark shale. East of this line the sands, with the exception of local areas indicated by *C–D* and *M–N*, contain no water. Toward the outcrop *H–B* fresh water occasionally occurs in the few wells drilled this far east. The Gordon sand in the central part of this area yields very small quantities of salt water after a well has been pumped for a number of years. The quantity of salt water is almost negligible, however, amounting on an average to about a barrel a week. With these exceptions the sands to all appearances are dry. This is verified by the fact that the oil almost invariably occurs in the synclines. In the two local areas above mentioned salt water appears in considerable quantities. These areas have no relation to the structural features of the basin as a whole, for they exist at places structurally 600 to 1,000 feet above the lower part of the basin. The sands are oil and gas-bearing in these areas and from all appearances resemble the Catskill sands elsewhere. The exact boundaries of the area in which no red shale occurs can not be defined exactly, but it is limited to the territory indicated by

[9] Munn, M. J., and Griswold, W. T., "Geology of Oil and Gas Fields in Stubenville, Burgettstown, and Claysville Quad.," Bull. U. S. Geol. Survey, No. 318, p. 16, 1907.

the lines *R–S* and *E–F*. As might be expected, every well that contains salt water in these areas may not show an absence of red material for there may have been some local movement of water along the sands.

EXPLANATION CONFORMS TO OTHER OBSERVATIONS.

The data given above appears to show a close relationship between absence of water and occurrence of red beds. When it is considered that the sands are dry to the east, where all the facts indicate subaërial deposits, and water-bearing to the westward, where they grade into marine deposits, it is but logical to conclude that the explanation of the absence of water is, as has been stated, due to the aëration of sediments of continental origin. This conclusion not only offers an explanation of the absence of water but adds corroborative evidence that the conditions of deposition and climate of the Catskill red beds were as Barrell[10] has described, that of a delta deposit formed in a semiarid, warm climate of seasonal rainfall, a conclusion which he bases on other physical and organic evidence. It also confirms his belief that the red beds of the Catskill and Mississippian were formed as a result of oxidation of the sediments after they were deposited, for on no other assumption could the close relation of the red beds and the sands be explained in the area under consideration.

There is a probability that the red color may have in part developed since the burial of the deposits as the air locked up in the sediments may have effected oxidation during the periods of geologic time which have elapsed since the Devonian. The absence of red color in some of the oil sands may be due to a number of factors in which low content of iron, the presence of organic material, and the short period of exposure to the atmosphere may have played a part. It is possible that some sands may have been depleted of water by the dry shale absorbing their water through capillary action.

The hypothesis of the origin of the dry sand and red beds is supported strongly by the data of other fields, for whenever oil

[10] Barrell, Joseph, "The Upper Devonian Delta of the Appalachian Geosyncline," 1913, *Amer. Jour. Sci.*, 4th ser., Vol. XXXVI., pp. 468–472.

ANALYSES OF SAMPLES OF BRINES COLLECTED IN WEST VIRGINIA AND PENNSYLVANIA.

Analyses made by S. C. Dinsmore, March 16, 1916.

Statement in Parts per Million (by Volume).

	1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
SiO_2	210	190	20	19	130	1,870	30	50	10	60	50	10
Fe	31.5	22	36	7.2	41	18	90	44	72	36	41	45
Al												
Ca	11,941	10,237	10,837	60	17,175	7,575	10,275	7,912	10,162	11,437	8,850	7,275
Mg	1,810	1,629	2,985	30	2,956	1,618	1,537	1,467	1,482	2,095	1,926	1,167
Na)								28,601				
K)	37,670	33,470	41,530	2,640	53,690	30,450	32,840	349	31,650	35,450	31,100	23,750
Co_3	0	0	0	0	0	0	0	0	0	0	0	0
HCO_3	44	12	26	102	4.8	95	34	29	51	61	73	0
SO_4	0	0	9.4	0	0	0	38	8.2	372	7.8	174	429
Cl	84,350	74,375	91,700	4,200	121,625	64,925	73,150	62,550	70,700	80,850	69,850	52,500
No_3				0								

Anal. 1. Sample No. 1. Russell Heirs, No. 2, Carter Oil Co., near Paden City, Wetzel County, W. Va., Big Injun sand, depth 1,425, 5 bbls. salt water daily.

Anal. 2. Sample No. 3. Fiel No. 2. E. A. Bradley, owner; Jackson township, Monroe County, Ohio. Big Injun sand, depth 1,355, 3 bbls. water daily.

Anal. 3. Sample No. 6. J. T. Craw, American Oil Company, Cave Run, Pleasants County, W. Va. Keener sand, depth 1,700.

Anal. 4. Sample No. 7. Cow Run well, American Oil Company, Cave Run, Pleasants County, W. Va. Depth 900, 2 bbls. water daily.

Anal. 5. Sample No. 9. Isaiah Baker, No. 1, South Penn Oil Company, Muddy Creek, Tyler County, W. Va. Big Injun sand, depth 2,000, 20 bbls. water daily.

Anal. 6. Sample No. 10. S. E. Elliott, No. 12, South Penn Oil Company, Bell Run, Lafayette district, Wirt County, W. Va. Salt sand, depth 1,600, 25 bbls. water daily.

Anal. 7. Sample No. LL. Maggie McDonald, No. 1, South Penn Oil Company, at McDonald, Allegheny County, Pa. Fifth sand, depth 2,200, ½ bbl. water daily.

Anal. 8. Sample No. 16. D. C. Rankin, well No. 1, Fairview township, Butler County, Pa. Fourth sand, depth 1,623–1,654, 1½ bbls. salt water daily. South Penn Oil Company.

Anal. 9. Sample No. 21. A. B. Kelly. well No. 19, Tionesta township, Forest County, Pa. Second sand, depth 948–964, 3 bbls. water daily.

Anal. 10. Sample No. 22. Lemmon farm, well No. 1, Pinegrove township, Venango County, Pa. Third sand, depth 1,006–1,024. Originally about 60 bbls. salt water daily, now 14 bbls. South Penn Oil Company.

Anal. 11. Sample No. 24. Prentice farm, well No. 16, Cranberry township, Venango County, Pa. Second sand, depth 622–645. Originally 15 bbls. salt water daily, now about 1 bbl. daily. South Penn Oil Company.

Anal. 12. Sample No. 25. Warrant 3802, well No. 2, Howe township, Forest County, Pa. Clarion sand, depth 709–731. Producing ½ bbl. salt water daily; would have produced 200 bbls. daily if not plugged. South Penn Oil Company.

sands occur in marine formations, as in the Trenton fields of Ohio and Indiana, the Gulf Coast, California, Baku, Roumania, and Galician fields, the sands contain great quantities of water, while in the fields of Wyoming, Utah, and Alberta, Canada, where the producing sands are closely associated with non-marine deposits, the sands contain less water. The Clinton sand, which is reported as non-water-bearing in most areas in Central Ohio, is closely associated with red strata. The occurrence of "red beds" with water-bearing sands in the mid-continent field of Kansas and Oklahoma is not contradictory to the conclusions here drawn, as in a recent investigation of the origin of the red beds in this area, Tomlinson[11] has reported them to be due to transported residual red soil.

FURTHER CONCLUSIONS.

Origin of Water.—If the dry sands have originated as explained, it follows that the brines still occurring in the sands at depths below the zone of active circulating ground waters are connate. The chemical nature of these brines are shown by the analyses (page 374) of 12 samples collected in connection with this study. On page 377 these brines are expressed in percentages of the total dissolved matter present. It will be noted that the brines show a close uniformity in the relative proportion of various salts present. When compared with ocean water it may be noted that they are from 3 to 7 times as concentrated, and that they are richer in chlorine and calcium and poorer in sulphates and sodium. How the transition from the ocean water to the brines has been effected is not the province of this paper to explain. Yet it may be pointed out that Washburne's[12] suggestion that the excess of chlorine has been added from deep-seated sources does not appear to be substantiated. Two brines, No. 7 and *B*, page 377, collected in the same locality but from sands occurring at a difference in depth of 4,000 feet show no

[11] Tomlinson, C. W., "The Origin of Red Beds. A Study of the Conditions of Origin of the Permo-Carboniferous and Triassic Red Beds of the Western United States," *Jour. Geol.*, Vol. XXIV., pp. 153–179, 238–253, 1916.

[12] Washburne, C. W., "Chlorides in Oil Field Waters," *Bull. Amer. Inst. Min. Eng.*, Vol. XLVIII., pp. 687–694, 1913.

TABLE EXPRESSING ANALYSES IN PER CENT. OF TOTAL SALTS PRESENT.

	SiO_2.	Fe.	Co.	Mg.	HCO_3.	SO_4.	Cl.	Na.	K.	Salinity.
1	.15	.02	8.77	1.33	.03		61.99	27.68		13.60565
2	.15	.01	8.53	1.35	.01		62.02	27.90		11.9935
3	.01	.02	7.29	2.02	.01	.006	62.28	28.26		14.72334
4	.26	.10	.85	.42	1.44		59.50	37.40		.70582
5	.06	.02	8.77	1.51	.002		62.17	27.44		10.5681
6	1.75	.01	7.10	1.53	.08		60.93	28.57		10.6551
7	.02	.07	8.70	1.30	.02	.03	61.14	27.83		11.7994
8	.04	.04	7.82	1.45	.02	.08	61.96	28.28	.34	10.11102
9	.008	.06	8.87	1.29	.04		61.74	27.64		11.4499
10	.04	.02	8.79	1.61	.04	.006	62.11	27.26		12.99968
11	.04	.03	7.96	1.73	.06	.15	62.02	27.97		11.1164
12	.01	.05	8.55	2.36		.50	61.40	27.88		8.5176
A	—	—	1.20	3.72	.21	7.69	55.29	30.59	1.11	10.56218
B	—	.06	9.56	.94	—	.02	61.34	24.50	1.97	26.36

For explanations of Nos. 1 to 12 see page 375.

A. A mean of 77 analyses of ocean water from many localities, collected by the Challenger Expedition. W. Dittman, Challenger Report, quoted by Clarke, "Data of Geochemistry," Bull. 616 U. S. Geol. Survey, p. 123, 1916.

B. Water from 6,300 depth in Peoples natural gas well, near McDonald, Pa.; analyses by G. Steiger in laboratory of U. S. Geol. Survey, from Clarke, idem, p. 183.

increase in chlorine at the greater depth which would be expected if the chlorine originated from such a source.

Movement of Water.—The movement of the water in the earth's strata and especially in oil-bearing sands has been the subject of much literature in consideration of the part it has played in the segregation and migration of oil. Some have held that there has been a widespread movement both across and along the strata. It is obvious, however, that, if the above explanation is correct, in the deeper sands in the area under consideration there has been no wide movement of the water or migration of the oil. Undoubtedly local movements due to adjustments to minor local structural features have occurred, but these were brought about during long geologic periods. Thus the liquids lying at these depths are to be considered as existing in a static condition. However, with the boring of wells to these sands, with the consequent escape of the oil and gas and the introduction of water through bore holes, this static state is destroyed and local movements occur along the strata. Another

conclusion that can be drawn is that there has not been, as Day[13] has suggested, in the eastern fields a migration of the heavier oils, presumably of Trenton age, upward across the strata which has produced by fractionation the lighter oils of the Devonian and Carboniferous sands. That this diffusion on theoretical ground could not occur through moist shale has been pointed out by Kalickij.[14] The distribution also of the water in the sands proves that there has been no such movement, for if there had been an upward movement of oil there could more easily have been one of water (water is less viscous and, due to its greater surface tension, has a greater capillary force than oil), which apparently has not occurred, for there are dry sands, *i. e.*, the Catskill, lying between prolific water-bearing strata.

SUMMARY.

There seems to be good evidence that the non-water-bearing sandstones of the Catskill formation in southwestern Pennsylvania and West Virginia were dried out by the semi-arid conditions which existed during Catskill time, which also brought about the formation of continental "red beds." In addition to this conclusion and partly resulting from it, the statement can be made that the facts observed do not substantiate the idea held by some geologists that there is a disappearance of water with depth. It is quite likely also that the brines found in oil fields and other deep-seated sedimentary strata are connate waters.

[13] Day, David T., "Diffusion of Oil through Fullers Earth," U. S. Geol. Survey, Bull. No. 365, 1908.

[14] Kalickij, K., "Über die Migration der Erdöls," *Bull. der Comite Geologique*, Vol. XIX., No. 7, p. 692, 1911.

VITA

Frank Reeves was born October 11, 1886, near Fairmont, West Virginia. His early training was received in the public schools of that city. His collegiate work was taken in Wooster University, Wooster, Ohio, and in the State University of West Virginia at Morgantown, where he received the degree of Balchelor of Arts in 1911. During the last four years he has been a student in the graduate department of geology at Johns Hopkins University, holding a Johns Hopkins University scholarship in the year 1915–1916.

He was employed during the field season of 1914 with a United States Geological Survey party in Ohio. The summer of 1915 was spent in the oil-fields of West Virginia and Pennsylvania, gathering data for the preparation of this dissertation.